

Constraints on cosmic ray and PeV neutrino production in blazars

B. Theodore Zhang and Zhuo Li

*Department of Astronomy, School of Physics, Peking University, Beijing 100871, China
Kavli Institute for Astronomy and Astrophysics, Peking University, Beijing 100871, China*

IceCube has detected a cumulative flux of PeV neutrinos, which origin is unknown. Blazars, active galactic nuclei with relativistic jets pointing to us, are long and widely expected to be one of the strong candidates of high energy neutrino sources. The neutrino production depends strongly on the cosmic ray power of blazar jets, which is largely unknown. The recent null results in stacking searches of neutrinos for several blazar samples by IceCube put upper limits on the neutrino fluxes from these blazars. Here we compute the cosmic ray power and PeV neutrino flux of Fermi-LAT blazars, and find that the upper limits for known blazar sources give stringent constraint on the cosmic ray loading factor of blazar jets (i.e., the ratio of the cosmic ray to bolometric radiation luminosity of blazar jets), $\xi_{\text{cr}} \lesssim (2 - 10)\zeta^{-1}$ (with $\zeta \lesssim 1$ the remained fraction of cosmic ray energy when propagate into the blazar broad line region) for flat cosmic ray spectrum, and that the cumulative PeV neutrino flux contributed by all-sky blazars is a fraction $\lesssim (10 - 50)\%$ of the IceCube detected flux.

I. INTRODUCTION

The first discovery of high energy cosmic neutrinos had been reported by IceCube collaboration [1–3]. In the latest result, IceCube reported the detection of 54 events beyond tens of TeV in the 4-yr search of high energy starting events (HESE) in the southern hemisphere, within which three are PeV energy scale, and the derived diffuse neutrino intensity for a flat spectrum from 60 TeV to 3 PeV is [4]

$$E_\nu^2 I_\nu = 0.84 \pm 0.3 \times 10^{-8} \text{ GeV cm}^{-2} \text{ s}^{-1} \text{ sr}^{-1} \quad (1)$$

The search for muon track events from the northern hemisphere resulted in a similar intensity above 100 TeV [5]. A track event from the northern sky with multi-PeV energy is even reported recently [6].

The origin of these high energy neutrinos is unknown, but believed to be related to cosmic ray (CR) production. Astrophysical accelerators in the universe produce the CRs which interact with radiation ($p\gamma$) and/or matter (pp) in the sources or during propagation after escape from the sources, and generate charged pions, which decay into neutrinos via $\pi \rightarrow \nu_\mu \mu$ and $\mu \rightarrow e \nu_e \nu_\mu$. In these processes, each neutrino carries $\sim 1/20Z$ energy of the primary CR, where Z is the charge number of the CR nuclei. The detection of PeV neutrinos implies that there should be some kinds of cosmic accelerators that can produce CRs up to $\sim 20Z$ PeV.

The arrival directions of the IceCube detected neutrinos are consistent with isotropic distribution [3]. The gamma-ray observations of diffuse Galactic emission and individual Galactic point sources by Fermi-LAT suggest that Galactic neutrino flux cannot account for the total flux IceCube detects [7]. These hint that the IceCube neutrinos are extragalactic origin, although some fraction could be Galactic origin [e.g. 8]. There are already many extragalactic objects proposed to produce CRs and neutrinos long before the IceCube detection [e.g., 9–14]. However, using the Fermi-LAT observations of those potential sources and simply assuming the gamma-ray to neutrino flux ratio is constant, [7, 15] suggested that gamma-ray bursts and flat spectrum radio quasars (FSRQs) may not account for the IceCube neutrino flux, but starburst galaxies are still possible.

Blazars are a class of strong candidate sources. They are the active galactic nuclei with relativistic jets pointing toward us, and consist of two subclasses, BL Lac objects (BL Lacs) and FSRQs. It is expected that the CRs produced by the jet interact with photons from or outside of the jet can produce pions and hence neutrinos. Many discussions are going on after the IceCube detection for whether blazars can account for the IceCube neutrinos [15–21].

Besides the detection of diffuse neutrinos, IceCube has also carried out deep search of neutrinos from individual astrophysical objects, including three groups of bright blazars [22, 23]. No signal is found but strong upper limit is put on the neutrino flux from individual blazars. In this work we use the flux upper limit to constrain the CR loading in blazar jets. Moreover, applying the CR loading factor to the population of blazars, which has been measured by Fermi-LAT [e.g., 24, 25], we obtain constraints on the all-sky neutrino flux from blazars. The results are compared with IceCube detected flux in order to test if blazars can produce the bulk of the IceCube PeV neutrinos. Hereafter we take the convention $Q = 10^x Q_x$ and use cgs units unless state otherwise.

II. NEUTRINO PRODUCTION PROCESSES

The blazar neutrino production models have been well established in the literatures. We adopt the same picture for neutrino production in blazars as Ref. [16], which is one of the latest updated models. CRs are produced in the blazar jets, and interact with the intense soft-photon field. There could be various sources of target photons; they may come from the jet, e.g., the synchrotron radiation from jet-accelerated electrons, whereas they may be the broad line emission from the broad line region (BLR) or the infrared emission from the dust torus. The neutrino production rate depends on the CR production of the jets and the photomeson production efficiency of CRs, which we will describe below.

We assume a connection between the CR and bolometric radiation luminosity from the jet as [16]. Since we are interested in the neutrino flux at $E_\nu \sim 1$ PeV, we focus on the CR production at $E_p \sim 20E_\nu \sim 20$ PeV (the factor 20 comes from that the photo-produced pion carries a fraction of $\sim 1/5$ of the primary proton energy, and that each lepton from pion decay carries $\sim 1/4$ of the pion energy). We define the CR luminosity from the jet at E_p as $E_p L_{E_p} \approx \hat{\xi}_{\text{cr}} L_{\text{rad}}$, where L_{rad} is the bolometric radiation luminosity of the jet, and $\hat{\xi}_{\text{cr}}$ is the CR loading factor for CRs at $E_p \simeq 20$ PeV. Ref [16] defines the total CR loading factor as $\xi_{\text{cr}} \equiv L_{\text{cr}}/L_{\text{rad}}$ where L_{cr} is the total CR luminosity. If the CR energy distribution is $dn/dE_p \propto E_p^{-p}$ for $E_{p,\text{min}} < E_p < E_{p,\text{max}}$ with $p \simeq 2$, then $\hat{\xi}_{\text{cr}} \simeq \xi_{\text{cr}}/\ln(E_{p,\text{max}}/E_{p,\text{min}}) \simeq \xi_{\text{cr}}/27.6$, where the last equation is for $E_{p,\text{max}} \sim 1$ ZeV, and $E_{p,\text{min}} \sim 1$ GeV. We assume the CR loading factor to be constant, and the case of deviation from constant will be discussed in the last section.

The flavor ratio of neutrinos produced by charged pion decay is $\nu_e : \nu_\mu : \nu_\tau = 1 : 2 : 0$. Due to mixing in propagation, the observed neutrinos show roughly equal flavor ratio of $\nu_e : \nu_\mu : \nu_\tau \approx 1 : 1 : 1$. The PeV per-flavor neutrino luminosity from the jet is given by

$$E_\nu L_{E_\nu} \approx \frac{1}{8} f_{p\gamma} E_p L_{E_p} \approx \frac{1}{8} f_{p\gamma} \hat{\xi}_{\text{cr}} L_{\text{rad}} \quad (2)$$

where $f_{p\gamma}$ is the photomeson production efficiency, and the factor $1/8$ comes from that half of the primary protons are channeled into charged pion production, and the four leptons from charged pion decay share equally the pion energy.

Because of the photo-produced Δ resonance, the protons with energy E'_p mainly interact with photons with energy that satisfies $E'_p E'_\gamma \approx 0.2 \text{ GeV}^2$, where both E'_p and E'_γ should be measured in the frame where photons are roughly isotropic. Therefore, target photons relevant to PeV neutrino production are mainly from the broad line emission and the synchrotron emission from the jet, other than the infrared photons from the dust torus (which are more relevant to EeV neutrino production). We derive the contributions to the photomeson production efficiency by the synchrotron emission and the broad line emission separately.

A. Synchrotron photon induced neutrino production

The jet can accelerate electrons which then generate synchrotron and inverse-Compton photons. In the same time, CR ions may also be accelerated in the jet and interact with the synchrotron photons. The CR and synchrotron photon interactions will happen unavoidably. Consider the interactions in the comoving frame of a blob of the jet. Given the observed jet radiation spectrum EL_E , the bulk Lorentz factor of the jet Γ_j , and the blob radius r_b , the comoving photon density, at comoving photon energy $\epsilon = E/\Gamma_j$, can be given by $\epsilon n_\epsilon \approx 3EL_E/4\pi r_b^2 c \Gamma_j E$.

The photomeson production efficiency in the blob, for CRs interacting with photons with energy ϵ , is $f_{p\gamma}^{\text{syn}} \approx \epsilon n_\epsilon \sigma_{p\gamma}^{\text{eff}} l_b$, where $\sigma_{p\gamma}^{\text{eff}}$ is the effective cross section, and l_b is the size of the blob in the comoving frame. Using the rectangular approximation to the $p\gamma$ cross section, we have $\sigma_{p\gamma}^{\text{eff}} \approx \kappa_\Delta \sigma_\Delta (\Delta \bar{\epsilon}_\Delta / \bar{\epsilon}_\Delta)$, with $\sigma_\Delta \approx 5 \times 10^{-28} \text{ cm}^2$, $\kappa_\Delta \approx 0.2$, $\bar{\epsilon}_\Delta \approx 0.34 \text{ GeV}$, and $\Delta \bar{\epsilon}_\Delta \approx 0.2 \text{ GeV}$. The typical dissipation radius is estimated to be $r_b \approx \Gamma_j l_b$, with $l_b \approx \Gamma_j c \delta t$. Here δt is the variability time in the black-hole frame. Hereafter $\Gamma_j = 10$ and $\delta t = 10^5 \text{ s}$ are used.

For the ~ 1 PeV neutrinos that we are interested in, the relevant target photon energy is $E \sim 1 \Gamma_{j,1}^2 (1 \text{ PeV}/E_\nu) \text{ keV}$, thus we need to know the radiation luminosity EL_E at $E = 1 \text{ keV}$, and then the photomeson production efficiency for CRs responsible to PeV neutrinos is

$$f_{p\gamma}^{\text{syn}} = 9.7 \times 10^{-6} \frac{EL_E(\text{keV})}{10^{45} \text{ erg s}^{-1}} \Gamma_{j,1}^{-4} \delta t_5^{-1}. \quad (3)$$

B. BLR photon induced neutrino production

The broad line emission originates from numerous small, cold and dense gas clouds, which are photoionized by the UV and X-rays from the accretion disk and hot plasma. The broad line emission mainly comes from $\text{H I Ly}\alpha$,

and has photon energy of $E_{\text{BL}} = 10.2$ eV in the black-hole rest frame. The corresponding neutrino energy, due to photo-produced Δ resonance, is just $E_\nu \sim 1(10\text{eV}/E_{\text{BL}})\text{PeV}$. The typical radius of the BLR is estimated to be $r_{\text{BLR}} \approx 10^{17}$ cm $L_{\text{AD},45}^{1/2}$ [26], where L_{AD} is the accretion-disk luminosity. The BLR luminosity is related to the accretion-disk luminosity through $L_{\text{BL}} \approx f_{\text{cov}} L_{\text{AD}}$, where f_{cov} is the covering factor of the gas clouds, and typically $f_{\text{cov}} = 0.1$ [27, 28]. The broad line photon density in the black-hole rest frame is $n_{\text{BL}} \approx L_{\text{BL}}/4\pi r_{\text{BLR}}^2 c E_{\text{BL}}$.

The CRs produced inside the BLR will propagate through the BLR, and unavoidably interact with the broad line photons and generate pions. The photomeson production efficiency in this process, in which PeV neutrinos are produced, is then $f_{p\gamma}^{\text{BLR}} \approx n_{\text{BL}} \sigma_{p\gamma}^{\text{eff}} r_{\text{BLR}}$, i.e.,

$$f_{p\gamma}^{\text{BLR}} = 9.6 \times 10^{-3} f_{\text{cov},-1} L_{\text{AD},45}^{1/2}. \quad (4)$$

The CRs can interact with both synchrotron and BLR photons to generate PeV neutrinos, and it can be seen that usually the efficiency induced by BLR photons is much higher than the one by synchrotron photons, $f_{p\gamma}^{\text{BLR}} \gg f_{p\gamma}^{\text{syn}}$.

The total photomeson production efficiency in eq.(2) is

$$f_{p\gamma} = f_{p\gamma}^{\text{syn}} + \zeta f_{p\gamma}^{\text{BLR}}, \quad (5)$$

where $\zeta < 1$ is the fraction of the CR energy after the energy loss before they propagate into the BLR. The energy loss could be due to, e.g., photomeson production by interactions with synchrotron photons, and adiabatic cooling, etc. Usually $f_{p\gamma}^{\text{syn}} \ll 1$ suggests that the former is negligible, then the latter is more relevant, i.e., $\zeta \gtrsim r_b/r_{\text{BLR}} \approx 0.3\Gamma_{j,1}^2 \delta t_5 L_{\text{AD},45}^{-1/2}$, where the lower limit holds if the CRs are confined in the blob until the blob travels to the BLR. So the PeV neutrino production is dominated by CR-BLR photon interactions, $\zeta f_{p\gamma}^{\text{BLR}} \gg f_{p\gamma}^{\text{syn}}$, as in Ref [16].

C. Blazar emission

In order to derive the neutrino luminosity $E_\nu L_{E_\nu}$ for a blazar with eqs. (2), (3), (4) and (5), we need its accretion disk luminosity L_{AD} , bolometric radiation luminosity L_{rad} , and specific luminosity at 1 keV $EL_E(\text{keV})$. For this purpose we follow the blazar emission model in ref. [16], which adopted the accretion-disk model of [29, 30] and the blazar sequence model of [31, 32]. Specifically, in order to derive the neutrino luminosity of Fermi-LAT detected blazars, we need L_{AD} , L_{rad} , and $EL_E(\text{keV})$ as functions of L_γ , the gamma-ray luminosity integrated over the spectrum above 100 MeV.

Ref [16] gives discrete values of L_{AD} and L_{rad} , and by linear fits we obtain

$$\begin{aligned} \log L_{\text{rad}} &= 1.1x - 2.2, \\ \log L_{\text{AD}} &= 1.3x - 16, \end{aligned}$$

where $x \equiv \log L_\gamma$, and the luminosities are in units of erg s^{-1} . The linear relations can be expected given the facts that gamma-ray luminosity is a significant fraction of the bolometric radiation luminosity, and that the bolometric radiation luminosity is roughly proportional to the accretion disk luminosity.

The keV luminosity depends on the blazar spectra, which are found to follow the blazar sequence model. The relation of $EL_E(\text{keV})$ with L_γ shows a weak function of L_γ at low L_γ , because of the fact that as the luminosity increases the synchrotron spectral peak moves to lower frequencies, and a maximum around $L_\gamma \sim 10^{49.6} \text{erg s}^{-1}$, due to the crossing of the synchrotron spectral peak at keV scale. We adopt a three segment fit to the relation, and obtain

$$\begin{aligned} \log EL_E(\text{keV}) &= 1.3 \times 10^{-14}x + 45 & x < 46 \\ &= 0.27x^2 - 25x + 630 & 46 < x < 49.6 \\ &= -0.92x + 93 & x > 49.6 \end{aligned}$$

Now for a blazar with its gamma-ray luminosity L_γ measured, the main uncertainty in deriving its PeV neutrino luminosity $E_\nu L_{E_\nu}$ is the unknown CR loading factor $\hat{\xi}_{\text{cr}}$. On the other hand, once L_γ and $E_\nu L_{E_\nu}$ are measured, $\hat{\xi}_{\text{cr}}$ can be determined or constrained. Note that unlike [15] which assumes simple proportionality of neutrino and gamma-ray luminosities, here L_{rad} and $f_{p\gamma}$ are not strict linear function of L_γ , so the neutrino luminosity $E_\nu L_{E_\nu}$ (eq. 2) is not strictly linear function of L_γ either.

It should be commented that the errors in the above three luminosity relations are all smaller than 0.3 dex. Moreover there may be uncertainty in the bulk Lorentz factor of jets Γ_j . If $\Gamma_j = 20$ then the relevant synchrotron photons for PeV neutrino production lie at 4 keV. We will discuss below the effects from the uncertainties of the luminosities and Γ_j .

III. CONSTRAINTS ON CR LOADING

IceCube had tried to search the muon track events from known blazars. They select three catalogs of blazars, i.e., 33 bright FSRQs, 27 low synchrotron peaked (LSP) BL Lacs, and 37 hard spectrum BL Lacs [22, 23]. All the searches result in non-detection, and put constraints on their neutrino flux. As for the 33 bright FSRQs that IceCube selected, all of them are compatible with the null hypothesis. The 90% confidence level upper limit for the combined $\nu_\mu + \bar{\nu}_\mu$ flux from the 33 FSRQs is [22, 23]

$$E_\nu^2 \Phi_{\nu_\mu + \bar{\nu}_\mu}^{90\%} = 3.46 \times 10^{-9} \text{ GeV cm}^{-2} \text{ s}^{-1}. \quad (6)$$

Note that a flat neutrino spectrum, $\Phi_\nu \propto E_\nu^{-2}$, is assumed in giving the upper limit. For the other assumed spectral profiles, the upper limit for the neutrino flux at PeV will change. For example, assume the spectral shape derived by Ref. [16], then the spectrum is harder, with the TeV-to-PeV slope roughly following $\Phi_\nu \propto E_\nu^{-1.23}$. Note also that the IceCube upper limits are resulted from stacking sources from both northern and southern hemispheres. IceCube in the south pole is more sensitive to northern point sources at TeV-to-PeV range, whereas less sensitive to southern sources. To be conservative we assume all stacked sources come from northern hemisphere. For track events from the northern hemisphere, the IceCube effective area in the relevant neutrino energy range can be approximated as $A_{\text{eff}}(E_\nu) \propto E_\nu$, then the upper limit for the neutrino flux at $E_\nu = 1 \text{ PeV}$ is, compared with that with flat spectrum assumed, enhanced by a factor of

$$f_\alpha = \frac{\int_{1 \text{ TeV}}^{1 \text{ PeV}} (E_\nu/1 \text{ PeV})^{-2} A_{\text{eff}}(E_\nu) dE_\nu}{\int_{1 \text{ TeV}}^{1 \text{ PeV}} (E_\nu/1 \text{ PeV})^{-1.23} A_{\text{eff}}(E_\nu) dE_\nu} = 5.3.$$

This factor is smaller if consider the much weaker sensitivity of IceCube for southern point sources. Unless stated otherwise, we consider in the following the IceCube upper limits with flat neutrino spectrum assumed, but the case of harder spectra will also be discussed.

We calculate the total neutrino flux from the 33 FSRQs, given their gamma-ray emission properties, then the CR loading factor $\hat{\xi}_{\text{cr}}$ can be constrained by the IceCube limit on the neutrino flux. The neutrino flux from a certain FSRQ is given by

$$E_\nu^2 \Phi_{\nu,i} = \frac{1}{8} f_{p\gamma}(L_{\gamma,i}) \frac{L_{\text{rad}}(L_{\gamma,i})}{L_{\gamma,i}} \hat{\xi}_{\text{cr}} S_{\gamma,i} \quad (7)$$

where $L_{\gamma,i}$ and $S_{\gamma,i}$ are its gamma-ray luminosity and observed flux, respectively, in the range of 0.1-100 GeV. In Table B.6 of [22], the photon number flux, the spectral photon indices and gamma-ray luminosity have been listed for these 33 FSRQs. We take the gamma-ray luminosity from the table (note they are calculated under the same cosmology model as we do later in the calculation of the diffuse neutrino intensity from blazars). We also take the gamma-ray flux from the table, but note that the table only gives the photon number flux of 1 GeV to 100 GeV, and we convert them to the gamma-ray flux S_γ of 100 MeV to 100 GeV with the given spectral photon indices (resulted from spectral fitting in 0.1-100 GeV range). The interactions with BLR photons dominate the production of PeV neutrinos for FSRQs, thus only eq (4) is relevant for the calculation of $f_{p\gamma}$. Using the observational limit in stacking search, eq (6), we obtain an upper limit on the CR loading factor;

$$\sum_i E_\nu^2 \Phi_{\nu,i} < E_\nu^2 \Phi_{\nu_\mu + \bar{\nu}_\mu}^{90\%} \Rightarrow \hat{\xi}_{\text{cr}} < 0.062 f_{\text{cov},-1}^{-1} \zeta^{-1}. \quad (8)$$

As for the total CR loading factor, we have $\xi_{\text{cr}} \simeq 27.6 \hat{\xi}_{\text{cr}} \lesssim 1.7 f_{\text{cov},-1}^{-1} \zeta^{-1}$ for flat CR spectrum, $p \simeq 2$.

With the same method we also constrain $\hat{\xi}_{\text{cr}}$ based on the upper limit that IceCube put on the neutrino flux of the 27 LSP BL Lacs, for which the gamma-ray properties have been shown in Table B.7 of [22]. The 90% confidence level upper limit for the $\nu_\mu + \bar{\nu}_\mu$ flux is [22] $E_\nu^2 \Phi_{\nu_\mu + \bar{\nu}_\mu}^{90\%} = 5.24 \times 10^{-9} \text{ GeV cm}^{-2} \text{ s}^{-1}$. In the calculation of neutrino flux from individual sources, we consider neutrino production induced by both BLR and synchrotron photons, but the contribution by synchrotron photon induced production is much smaller, thus the constraint on $\hat{\xi}_{\text{cr}}$ mainly results from the BLR induced neutrinos. Our result gives $\hat{\xi}_{\text{cr}} < 0.92 \zeta^{-1}$, and hence $\xi_{\text{cr}} \lesssim 25 \zeta^{-1}$. The constraint is much less stringent than using FSRQs, because LSP BL Lacs are weaker neutrino producers. We do not expect FSRQs and BL Lacs are different in CR production mechanisms, so the CR loading factors should depend on intrinsic physics of jets. In the following we apply the more stringent constraint, eq (8), to both FSRQs and BL Lacs, and calculate their contribution to the diffuse neutrinos. It should be noted that if assuming a harder sub-PeV neutrino spectrum like in Ref. [16], the upper limits to the CR loading factor (eq.8) is increased by a factor of $f_\alpha = 5.3$, i.e., $\hat{\xi}_{\text{cr}} < 0.33 \zeta^{-1}$ and $\xi_{\text{cr}} \lesssim 9 \zeta^{-1}$.

IV. CONSTRAINTS ON DIFFUSE PEV NEUTRINOS FROM BLAZARS

Since the blazar neutrino luminosity $E_\nu L_{E_\nu}(L_\gamma; \hat{\xi}_{\text{cr}})$ can be calculated as above given the gamma-ray luminosity L_γ and the CR loading factor $\hat{\xi}_{\text{cr}}$, the all-sky neutrino flux from all blazars should depend on the redshift and gamma-ray luminosity distribution of blazars, which has been measured recently thanks to the deep all-sky survey by Fermi-LAT [24, 25]. The observed diffuse neutrino intensity is the sum of all blazar contribution in the universe, and is given by [e.g., 24]

$$E_\nu^2 I_\nu = \frac{c}{4\pi H_0} \int_{z_{\min}}^{z_{\max}} dz \frac{1}{(1+z)^2 \sqrt{(1+z)^3 \Omega_m + \Omega_\Lambda}} \times \int_{L_{\gamma, \min}}^{L_{\gamma, \max}} dL_\gamma \int_{\Gamma_{\min}}^{\Gamma_{\max}} d\Gamma \frac{d\rho}{dL_\gamma} E_\nu L_{E_\nu}, \quad (9)$$

where $E_\nu L_{E_\nu}$ is the neutrino luminosity from one blazar, given by eq. (2), and $d\rho/dL_\gamma$ is the blazar density in the universe. Following [24, 25], here we consider $d\rho(z, L_\gamma, \Gamma)/dL_\gamma$ as function of not only the redshift z and gamma-ray luminosity L_γ , but also the spectral photon index Γ in gamma-rays, thus $d\rho(z, L_\gamma, \Gamma)/dL_\gamma$ is the blazar number per unit comoving volume per unit luminosity and per unit Γ . For the cosmology we take $H_0 = 67.8 \text{ km s}^{-1} \text{ Mpc}^{-1}$, $\Omega_m = 0.315$, and $\Omega_\Lambda = 0.685$.

FSRQs contribution. We consider the diffuse PeV neutrinos from FSRQs first. We adopt the redshift and luminosity distributions of FSRQs $d\rho/dL_\gamma$ from [24], which shows that the luminosity-dependent density evolution (LDDE) model gives the best fit among the others to the Fermi-LAT data. The LDDE model is parameterized as:

$$\frac{d\rho}{dL_\gamma}(L_\gamma, z, \Gamma) = \Phi(L_\gamma) \times e(z, L_\gamma) \times e^{-\frac{(\Gamma-\mu)^2}{2\sigma^2}},$$

$$\Phi(L_\gamma) = \frac{A}{\ln(10)L_\gamma} \left[\left(\frac{L_\gamma}{L_*} \right)^{\gamma_1} + \left(\frac{L_\gamma}{L_*} \right)^{\gamma_2} \right]^{-1},$$

$$e(z, L_\gamma) = \left[\left(\frac{1+z}{1+z_c(L_\gamma)} \right)^{p_1} + \left(\frac{1+z}{1+z_c(L_\gamma)} \right)^{p_2} \right]^{-1},$$

with $z_c(L_\gamma) = z_c^*(L_\gamma/10^{48})^\alpha$. Here $z_c(L_\gamma)$ corresponds to the redshift where the evolution changes signs. For the best fit the parameter values are: $A = 3.06 \times 10^{-9} \text{ Mpc}^{-3}$, $\gamma_1 = 0.21$, $L_* = 0.84 \times 10^{48} \text{ erg s}^{-1}$, $\gamma_2 = 1.58$, $z_c^* = 1.47$, $\alpha = 0.21$, $p_1 = 7.35$, $p_2 = -6.51$, $\mu = 2.44$, and $\sigma = 0.18$. The integration range is as follows: for the redshift range $z_{\min} = 0.01$ and $z_{\max} = 6$; for the luminosity range $L_{\gamma, \min} = 10^{44} \text{ erg s}^{-1}$ and $L_{\gamma, \max} = 10^{52} \text{ erg s}^{-1}$; and for the photon index range $\Gamma_{\min} = 1.8$ and $\Gamma_{\max} = 3.0$.

Using eq (8), the derived diffuse PeV neutrino intensity (per flavor) from FSRQs induced by BLR photons is

$$E_\nu^2 I_\nu < 0.74 \times 10^{-9} \text{ GeV cm}^{-2} \text{ s}^{-1} \text{ sr}^{-1} \quad (10)$$

(note ζ is canceled out) whereas that induced by synchrotron photons is $E_\nu^2 I_\nu < 1.49 \times 10^{-12} \zeta^{-1} \text{ GeV cm}^{-2} \text{ s}^{-1} \text{ sr}^{-1}$. The FSRQ neutrino production is dominated by that induced by BLR photons, but the upper limit on their diffuse flux is only a fraction $< 8.8\%$ of the IceCube detected flux (eq. 1).

BL Lac contribution. Next consider LSP BL Lac objects. The density distribution of LSP BL Lacs is taken from [25], which also shows that the LDDE model provides a better representation of the data:

$$\frac{d\rho}{dL_\gamma}(L_\gamma, z, \Gamma) = \Phi(L_\gamma, z=0, \Gamma) \times e(z, L_\gamma),$$

$$\Phi(L_\gamma, z=0, \Gamma) = \Phi(L_\gamma) \times e^{-\frac{(\Gamma-\mu(L_\gamma))^2}{2\sigma^2}},$$

$$e(z, L_\gamma) = \left[\left(\frac{1+z}{1+z_c(L_\gamma)} \right)^{p_1(L_\gamma)} + \left(\frac{1+z}{1+z_c(L_\gamma)} \right)^{p_2} \right]^{-1},$$

TABLE I: Upper limits for the diffuse PeV neutrino intensity $E_\nu^2 I_\nu$ from different types of blazars.

Blazar type	$\hat{\xi}_{\text{cr}}\zeta$	BLR	Synchr	Fraction
FSRQ	0.062	0.74×10^{-9}	$1.49 \times 10^{-12}\zeta^{-1}$	0.088
LSP BL Lac	0.92	1.45×10^{-9}	$1.18 \times 10^{-12}\zeta^{-1}$	0.17
	0.062	9.94×10^{-11}	$7.98 \times 10^{-14}\zeta^{-1}$	0.012
HSP+ISP BL Lac	0.92		$4.12 \times 10^{-12}\zeta^{-1}$	$4.9 \times 10^{-4}\zeta^{-1}$
	0.062		$2.78 \times 10^{-13}\zeta^{-1}$	$3.3 \times 10^{-5}\zeta^{-1}$

Notes. All intensities are in unit of $\text{GeV cm}^{-2}\text{s}^{-1}\text{sr}^{-1}$. The last column is the fraction of the blazar diffuse neutrino intensity within the IceCube detected intensity (eq. 1).

where $\mu(L_\gamma) = \mu^* + \beta \times (\log(L_\gamma) - 46)$, $p_1(L_\gamma) = p_1^* + \tau \times (\log(L_\gamma) - 46)$, and $z_c(L_\gamma) = z_c^*(L_\gamma/10^{48})^\alpha$. The values of parameters from the best fit are: $A = 3.34 \times 10^{-10} \text{ Mpc}^{-3}$, $\gamma_1 = 0.48$, $\gamma_2 = 6.33$, $L_* = 1.48 \times 10^{48} \text{ erg s}^{-1}$, $z_c^* = 0.96$, $\alpha = -1.73 \times 10^{-3}$, $p_1^* = 4.10$, $\tau = 5.34$, $p_2 = -5.53$, $\mu^* = 2.32$, $\beta = -3.24 \times 10^{-2}$, and $\sigma = 0.23$. The integration ranges are, for redshift $z_{\min} = 0.03$ and $z_{\max} = 6$; for luminosity $L_{\gamma,\min} = 7 \times 10^{43} \text{ erg s}^{-1}$ and $L_{\gamma,\max} = 10^{52} \text{ erg s}^{-1}$; and for photon index $\Gamma_{\min} = 1.45$ and $\Gamma_{\max} = 2.80$. With eq (8) the derived diffuse PeV neutrino intensity (per flavor) from LSP BL Lacs is, for neutrinos induced by BLR photons, $E_\nu^2 I_\nu < 9.94 \times 10^{-11} \text{ GeV cm}^{-2}\text{s}^{-1}\text{sr}^{-1}$, whereas for that induced by synchrotron photons, $E_\nu^2 I_\nu < 7.98 \times 10^{-14} \zeta^{-1} \text{ GeV cm}^{-2}\text{s}^{-1}\text{sr}^{-1}$.

Finally we consider the diffuse neutrinos contributed by high and intermediate synchrotron peaked (HSP, ISP) BL Lacs. Their density distribution is described by the same LDDE model as LSP BL Lacs, but the best fit parameter values are different [25]: $A = 29.1 \times 10^{-10} \text{ Mpc}^{-3}$, $\gamma_1 = 0.22$, $\gamma_2 = 2.10$, $L_* = 0.26 \times 10^{48} \text{ erg s}^{-1}$, $z_c^* = 1.46$, $\alpha = 9.41 \times 10^{-2}$, $p_1^* = 1.98$, $\tau = 6.38$, $p_2 = -8.29$, $\mu^* = 2.05$, $\beta = 5.55 \times 10^{-2}$, and $\sigma = 0.24$. For the integration limits we use: $z_{\min} = 0.03$, $z_{\max} = 6$, $L_{\gamma,\min} = 7 \times 10^{43} \text{ erg s}^{-1}$, $L_{\gamma,\max} = 10^{52} \text{ erg s}^{-1}$, $\Gamma_{\min} = 1.45$, and $\Gamma_{\max} = 2.80$. The derived diffuse PeV neutrino flux (per flavor) induced by synchrotron photons for HSP and ISP BL Lacs is, with eq (8), $E_\nu^2 I_\nu < 2.78 \times 10^{-13} \zeta^{-1} \text{ GeV cm}^{-2}\text{s}^{-1}\text{sr}^{-1}$. We have neglected the neutrino production in BLR, because the broad line emission is weak in HSP and ISP BL Lacs. We can see that the neutrino flux from BL Lacs are many orders of magnitude smaller than the IceCube detection (eq. 1).

We summarize in Table I the constraints on $\hat{\xi}_{\text{cr}}$ for different blazar groups, and hence their contributions to the diffuse PeV neutrino intensity.

Let us discuss the model uncertainties in our derivation of the diffuse neutrino flux from blazars. (1) If assume a harder sub-PeV neutrino spectrum, all the upper limits for the diffuse PeV neutrino intensities should be increased by the same factor f_α as the CR loading factor. For $f_\alpha = 5.3$, the limit for the diffuse neutrino intensity of FSRQs (eq. 10) becomes $E_\nu^2 I_\nu < 0.39 \times 10^{-8} \text{ GeV cm}^{-2}\text{s}^{-1}\text{sr}^{-1}$, only a fraction $< 47\%$ of the IceCube detection.

(2) There is uncertainty in the measured blazar density distribution $d\rho/dL_\gamma$. However, this only leads to the uncertainty of the derived total neutrino intensity similar to that of derived gamma-ray background intensity, i.e., a factor of $\sim 20\%$ [24, 25].

(3) Some parameter values have been fixed in the calculation. The f_{cov} value affects the constraint on $\hat{\xi}_{\text{cr}}$, but it is canceled out in deriving the diffuse neutrino flux. The values of Γ_j and δt do affect the all-sky flux of synchrotron photon induced neutrinos, but the change should be within orders of magnitude. For example, if $\Gamma_j = 20$, the relevant photon energy for PeV neutrinos is $E = 4 \text{ keV}$. We derive again the EL_E and L_γ relation, and then calculate the synchrotron photon induced neutrino flux $E_\nu^2 I_\nu$ from FSRQs, LSP BL Lac, and HSP+ISP BL Lac, which are changed by a factor of 2, 0.9, and 0.4, respectively. Thus the conclusion that the diffuse PeV neutrino flux induced by synchrotron photons is smaller than the IceCube flux by many orders of magnitude does not change.

(4) There may be effect from the uncertainties in the relations of L_γ with L_{AD} and L_{rad} . The constraint of $\hat{\xi}_{\text{cr}}$ with FSRQ samples does depend on determinations of L_{AD} and L_{rad} , however, as seen by comparing eqs. (8) and (9), the dependence is largely canceled out in deriving the diffuse intensity of BLR induced neutrinos. For example, we have arbitrarily change L_{rad} by a factor of 3 to $1/3$, the upper limit on $\hat{\xi}_{\text{cr}}$ (eq. 8) varies from 0.02 to 0.18, and the upper limit on $E_\nu^2 I_\nu$ of FSRQs (eq.10) from 0.78 to $0.69 \times 10^{-9} \text{ GeV cm}^{-2}\text{s}^{-1}\text{sr}^{-1}$. Also, we change L_{AD} by a factor of 3 to $1/3$, the upper limit on $\hat{\xi}_{\text{cr}}$ (eq. 8) varies from 0.034 to 0.1, and the upper limit on $E_\nu^2 I_\nu$ of FSRQs from 0.72 to $0.71 \times 10^{-9} \text{ GeV cm}^{-2}\text{s}^{-1}\text{sr}^{-1}$. So the limit on the all-sky neutrino flux induced by BLR photons is hardly affected by the uncertainty in determining L_{AD} and L_{rad} . Note the relations of L_{AD} and L_{rad} with L_γ hardly depend on the adopted blazar sequence model, which is still under debate [e.g., 33].

V. SUMMARY AND DISCUSSION

We have used three observational results to constrain the diffuse PeV neutrino intensity from blazars, i.e., (1) the constraint of neutrino flux from known blazars in stacking searches by IceCube, (2) the measured gamma-ray flux from these known blazars by Fermi-LAT, and (3) the density distribution of blazars in the universe measured by Fermi-LAT. We first use results (1) and (2) to constrain the CR loading factor $\hat{\xi}_{\text{cr}}$ of FSRQs. The result indicates that the total CR loading is small, $\xi_{\text{cr}} \equiv L_{\text{cr}}/L_{\text{rad}} \lesssim 2\zeta^{-1}$ for flat CR spectrum. Given that the physics of CR production in blazar jet is expected to be intrinsically the same, the constraint of $\hat{\xi}_{\text{cr}}$ is applied to BL Lacs as well. With result (3) we then derive the diffuse PeV neutrino intensity from blazars (Table I). We find that blazar neutrinos, dominated by FSRQs, can only contribute $\lesssim 10\%$ of the diffuse PeV neutrino intensity (eq. 1). The conclusion is consistent with the result by simply assuming constant ratio of neutrino to gamma-ray flux from blazars [15].

If the cumulative neutrino spectrum from blazars is as hard as that of Ref. [16], the conclusions become that the total CR loading is $\xi_{\text{cr}} \lesssim 10$ and that the fraction of diffuse PeV neutrino flux contributed by blazars is $\lesssim 0.5$. These are consistent with Ref. [16] which suggests that $\xi_{\text{cr}} = 30 - 300$ is required for blazars to account for the IceCube detection, with the lower limit for the case of flat CR spectrum.

A. Caveats

Some comments should be made here regarding the hypotheses in the derivation.

First, we simply assume that the CR loading factor $\hat{\xi}_{\text{cr}}$ is a constant, which may not be true. There have been some research shows that the radiative efficiency may be lower for higher luminosity [26, 34], which implies that $\hat{\xi}_{\text{cr}}$ may weakly increase with L_{rad} [16] and hence L_{γ} . The blazars in the stacking searches of neutrinos by IceCube are mostly bright blazars, i.e., with high gamma-ray luminosity and/or small distance, thus the constraint to $\hat{\xi}_{\text{cr}}$ (eq. 8) is mainly valid to bright blazars. If the weak blazars are with smaller $\hat{\xi}_{\text{cr}}$ then the derived upper limit for the diffuse neutrino intensity from blazars is even lower, since the main contribution comes from lower luminosity and/or farther blazars. This leads to even stronger conclusion that blazars cannot contribute to the IceCube detection. The constraint is not valid if $\hat{\xi}_{\text{cr}}$ decreases strangely as the detected gamma-ray flux increases.

Second, the CR loading factor for BL Lacs may be different from that of FSRQs. However it should be $\sim 10^2$ times larger than constrained by stacked FSRQs, in order for BL Lacs to account for the IceCube flux. The constraint from 27 LSP BL Lacs, $\hat{\xi}_{\text{cr}} < 0.92\zeta^{-1}$, does not agree so.

Third, some notes should be made here regarding the possible effects of electromagnetic cascade on the estimate of the bolometric radiation luminosity, and hence the cosmic ray luminosity. The cascade may happen inside the sources, thus part of the high energy gamma-rays is re-emitted in lower than Fermi-LAT energy range. Our approach essentially takes the cascade into account, because the cascade component will be a part of the bolometric radiation luminosity.

On the other hand, the cascade may happen outside of the sources, i.e., in the cosmic radiation background (CRB). However, the effect can be neglected because: first, the 0.1-100 GeV gamma-rays hardly suffer from absorption in the CRB, and the cascade basically ends at < 100 GeV; secondly, the IceCube measured neutrino flux, much smaller than the all-sky integrated blazar 0.1-100 GeV gamma-ray flux, implies that the cascade component is negligible compared to the 0.1-100 GeV gamma-ray flux. Thus, the 0.1-100 GeV luminosity provides a good estimate of the bolometric radiation luminosity. On the contrary, if the cascade in propagation did happen seriously, the bolometric radiation luminosity should be much larger than estimated from the observed gamma-ray flux, then the constraint on $\hat{\xi}_{\text{cr}}$ by the same stacking limit for the neutrino flux should be much more stringent, since the neutrino luminosity is proportional to $\hat{\xi}_{\text{cr}}L_{\text{rad}}$. This does not weaken our constraints but backward.

Finally, one may worry that there could be bias for the sample we use because all these blazars are bright ones with high detected gamma-ray flux. However, if the assumption that CR loading factor $\hat{\xi}_{\text{cr}}$ is roughly a constant holds then our constraint on $\hat{\xi}_{\text{cr}}$ is valid no matter apparently bright or dim sample is used.

B. Comments on recent works

Our conclusion appears to be in conflict with some recent results. It is recently reported [20] that a high-fluence outburst of a FSRQ, PKS B1424-418, occurred in temporal and positional coincidence with the third PeV neutrino event detected by IceCube, indicating a direct physical association between them. The about 1-yr outburst duration and the IceCube effect area imply that the PeV neutrino flux is comparable to the gamma-ray flux during the outburst,

TABLE II: Comparison of the total flux of gamma-rays and neutrinos for the three blazar catalogs.

Blazar catalog	S_γ	S_γ	$E_\nu^2 \Phi_{\nu_\mu + \bar{\nu}_\mu}^{90\%}$
	10-100GeV	0.1-100GeV	$\sim 0.1-1\text{PeV}$
FSRQ		4.08×10^{-6}	3.46×10^{-9}
LSP BL Lac	8.41×10^{-9}	1.31×10^{-6}	5.24×10^{-9}
Hard-spectrum BL Lac	4.09×10^{-8}	2.76×10^{-6}	3.73×10^{-9}

Notes. All flux is in unit of $\text{GeV cm}^{-2} \text{s}^{-1}$. The detailed lists of the three catalogs, 33 FSRQs, 27 LSP BL Lacs and 37 hard gamma-ray spectrum BL Lacs, are shown in Tables B.6, B.7 and B.8, respectively, of [22].

$S_\nu \sim S_\gamma \sim 10^{-7} \text{GeV cm}^{-2} \text{s}^{-1}$ [20]. However, this seems to be in conflict with two observational results: (1) as pointed out by [15], the IceCube detected diffuse neutrino flux (20TeV-2PeV) is only 4% of the diffuse gamma-ray flux (0.1-100GeV) from FSRQs; and (2) the stacking analysis by IceCube for the catalog of 33 FSRQs even shows that the neutrino flux [23] is only $\lesssim 10^{-3}$ of their gamma-ray one (see Table II).

One may argue that the physical condition of the jet may change with the outburst, especially the CR loading power. In the outburst, with eq. (7) one finds $\hat{\xi}_{\text{cr}} \sim 8/f_{p\gamma}$, a factor $\gtrsim 8/0.062 \sim 130$ larger than usual. Since L_γ increases by 15-30 in the outburst [20], the CR luminosity ($L_{\text{cr}} \propto \hat{\xi}_{\text{cr}} L_\gamma$) increases at least by $(2-4) \times 10^3$'s accordingly, which is a dramatically large contrast. PKS B1424-418 is indeed in the FSRQ catalog for the track event search, with much larger effect area than the HESE analysis at the source location, so it is important to see if more PeV events can be found in the track-event data during the outburst.

It is also suggested that for BL Lacs as a class to explain the PeV neutrinos detected by IceCube, the neutrino flux from BL Lacs is required to be comparable or larger than the gamma-ray flux above 10 GeV, $S_\nu \gtrsim S_\gamma(> 10\text{GeV})$ [18]. However, the comparison of Fermi-LAT and IceCube observations to two catalogs of BL Lacs (Table II) shows that the BL Lac neutrino flux is, on the contrary, smaller than their gamma-ray one.

A very latest investigation by IceCube collaboration [35] contains the sample from the 2nd Fermi-LAT AGN catalogue (2LAC). Still no excess is observed and upper limits for cumulative neutrino flux of the resolved blazar population is obtained. Only by assuming the proportionality of gamma-ray and neutrino flux can they extrapolate the upper limit to the all-sky blazars including the unresolved blazars in gamma-ray observation. Their conclusion that 2LAC blazars contribute no more than 50% of the observed neutrinos if the spectral index is as hard as -2.2 is consistent with ours.

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